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13. ABSTRACT *(Maximum 200 words)*

We propose a novel field-effect semiconductor laser whose wavelength can be tuned by an electric field parallel to the growth direction of two tightly coupled quantum wells in the active region. We have demonstrated the concept by optically pumping a laser heterostructure whose active region consisted of two 50 Å GaAs wells separated by a 20 Å $Ga_{0.77}Al_{0.23}As$ potential barrier, in which, at 5 K, we have achieved tuning of the stimulated emission by more than 7 nm.

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Tunable coupled-quantum-well laser controlled by an electric field

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We propose a novel field-effect semiconductor laser whose wavelength can be tuned by an electric field parallel to the growth direction of two tightly coupled quantum wells in the active region. We have demonstrated the concept by optically pumping a laser heterostructure whose active region consisted of two 50 Å GaAs wells separated by a 20 Å $Ga_{0.77}Al_{0.23}As$ potential barrier, in which, at 5 K, we have achieved tuning of the stimulated emission by more than 7 nm.

The modulation of semiconductor lasers is highly attractive for optical communications and optical processing. Typically laser diodes are modulated by varying the injected current, but in that modulation scheme they are ultimately limited in speed by carrier lifetimes in their active layer. Certain field-effect lasers should be good candidates for circumventing such lifetime limitations because modulation in those lasers would not require a change in the total number of carriers. Furthermore, these lasers might be designed to require less charge transfer for their operation and hence would have shorter charging time constants.

Field-controlled light emission from quantum-well lasers was proposed[1,2] some time ago, but relatively little experimental work has been reported. The devices would operate by modulating the optical transition energies of a quantum well and by changing the electron-hole overlap inside the active area. Both wavelength tunability and intensity modulation of the emitted light are expected. Until now however, only intensity modulation, and in a limited form, has been reported. Field-induced gain switching at 40 K of an optically pumped quantum well laser has been shown,[3] and intensity modulation of light emitting diodes has been demonstrated by using an electric field to change the radiative recombination lifetime (or equivalently, the electron-hole overlap).[4] In these works switching could be accomplished between an "on" state when the field was zero and an "off" state when the field was applied, but to our knowledge, wavelength tuning of semiconductor lasers, and in general, optical devices in which lasing occurs while a significant electric field is being applied onto the gain medium, have not been reported. This absence is probably due to the substantial fields that would be required in a quantum-well laser and the practical difficulty of applying them in the presence of electric-field screening induced by the large number of carriers needed for lasing.

Taking advantage of the large energy shifts that even moderate fields produce on the optical transitions of coupled quantum wells, we demonstrate in this letter a quantum-well laser whose wavelength is tuned significantly by an external electric field. Specifically, we show tuning over more than 7 nm at 5 K in an optically pumped laser whose active region contains two GaAs quantum wells, each 50 Å wide, separated by a 20 Å $Ga_{0.77}Al_{0.23}As$ barrier. Intensity modulation should also be possible by exploiting the observed dependence of the lasing threshold on the applied field.

Coupled quantum wells (CQW), which have been studied extensively[5–7] in the last few years, offer for comparable electric fields, a larger tunability of their energy transitions than that provided by the Stark effect in single quantum wells.[1,8] In addition, the photoluminescence (PL) intensity from coupled quantum wells can be made to be relatively constant over a large range of fields and the shift of the PL spectrum linear as a function of field.[9] Figure 1(a) shows the zero-field potential profile and the electron and heavy-hole squared wave functions of a symmetric CQW structure formed by two wells, 50 Å wide, separated by a 20 Å barrier. Because of the coupling between the wells, the doubly degenerate ground state electronic wave function is split into symmetric and antisymmetric ones; the same occurs for the hole ground state. Optical transitions can take place between states in the valence and conduction bands, the lowest-energy of which, is dominant in light-emission processes.

When a longitudinal (i.e., along the direction of quantization) electric field is applied, the energy levels are modified and the wave functions are increasingly localized in separate wells, as sketched in Fig. 1(b). Consequently, the energy of the lowest transition decreases quasi-linearly with the field. This is a spatially indirect transition, in that it occurs between states whose wave functions are spatially separated, with the hole state fully localized in an individual well even for moderate fields and the electron state mostly confined in the other well, but with a finite overlap between the electron and hole wave functions. There are additional possible transitions, at higher energy: two direct ones (that in the high-field limit become degenerate and whose energy is field independent) involving electrons and holes in the same well and an indirect one between cross-well states. The ground-state indirect transition, although weak in absorption processes, dominates in emission as long as the coupling interaction of the electrons is larger than the thermal energy, kT.

We propose here a new field-effect tunable semiconductor laser[10] that takes advantage of the energy variation of the indirect, ground-state transition of two coupled quantum wells under an electric field. We have demon-

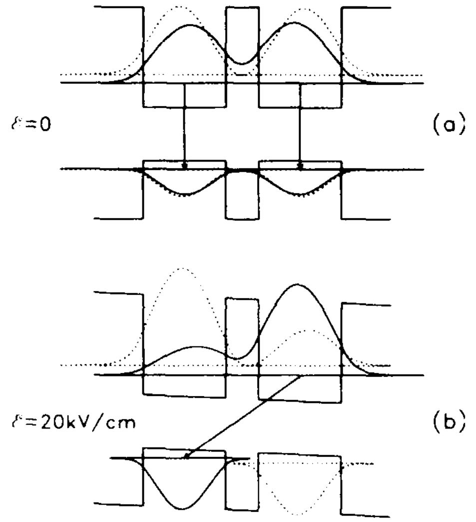

FIG. 1. Potential profile, energy levels, and electronic probabilities (wave functions squared) for a double quantum well structure with 50 Å GaAs well and a 20 Å $Al_xGa_{1-x}As$ barrier calculated for (a) flat-band conditions and (b) an applied electric field of 20 kV/cm. The arrows show the lowest energy transitions dominant in emission.

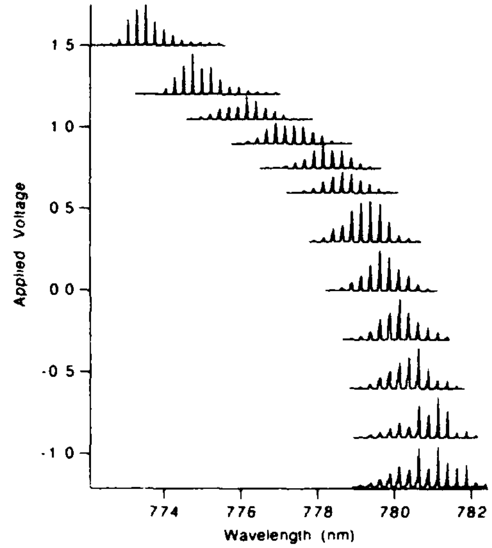

FIG. 2. Lasing spectral intensity as a function of applied voltage for a 300 μm device with coated ($R=90\%$) facets and a coupled-quantum-well active region consisting of two 50 Å GaAs layers separated by a 20 Å $Al_{0.23}Ga_{0.77}As$ barrier. The zero level of each spectrum corresponds to the value of the applied voltage shown on the ordinate. The intensities were scaled so that the different curves would not overlap.

strated the feasibility of the concept by imbedding a coupled well in a graded index separate confinement heterostructure (GRINSCH) similar to those previously used for single quantum well ridge lasers.[11] The different layers of the structure were deposited by molecular beam epitaxy on an n^+-GaAs substrate. The active region of the laser consisted of two 50 Å GaAs wells coupled by a 20 Å wide $Al_{0.23}Ga_{0.77}As$ barrier imbedded in a GRINSCH. Thick n- and p-type $Al_{0.63}Ga_{0.37}As$ cladding layers provided the optical confinement as well as a means to apply an electric field to the coupled wells. Electrical contact was provided by evaporating contacts on the n- and p-surfaces, with the p-contact in the form of 50 μm wide stripes so as to allow for optical pumping. Finally, laser cavities were made by cleaving the sample into bars corresponding to 300 μm device lengths. High reflectivity (90%) facet coatings were deposited on some of the devices to lower the threshold carrier densities. For comparison, measurements were also made on samples with uncoated facets.

The devices were pumped with 10 ps pulses at 100 MHz repetition rate from a mode locked Ti:Al_2O_3 laser. The excitation wavelength, 7600 Å, was selected so that electron-hole pairs were generated exclusively inside the wells. Pumping carriers into the cladding regions or the graded regions would lead to excessive photocurrent at nonzero fields, which in turn could lead to severe degradation of the device. The mode-locked nature of the pump allowed higher carrier densities to be attained as compared to the densities achievable with the same amount of average cw power. It also served to diminish any heating effects that might have been present. Such effects were further diminished by chopping the pump to less than 1% duty cycle using an acousto-optic modulator.

Samples were mounted inside a variable temperature cryostat and cooled with cold helium vapor. The electric field was applied by varying the bias across the p-i-n diode. The pump beam was focused onto the sample using a pair of crossed cylindrical lenses. Photoluminescence signal or stimulated emission coming out of the sample facets was collected by a lens and sent to a 0.75 m double spectrometer. Lasing was determined by an abrupt increase in output power and also by the presence of the many Fabry–Perot modes typical of a gain-guided semiconductor laser with a modulated (mode-locked) pump.

In Fig. 2, the laser spectra of a 300 μm long coated device at 5 K are shown for different applied voltages. As the voltage is decreased from 1.5 V (near-flat band) to −1.2 V, the laser output tunes a total of 7.5 nm (around 3 THz). For voltages above 1.2 V, the lasing wavelength tunes asymptotically toward the flat band lasing wavelength of 773.5 nm. Between 1.2 and 0.3 V, however, the tuning is quite linear. Finally at around 0.3 V the tuning begins to saturate, and at −0.9 V the saturation is complete. To provide the output power dependence on voltage and to ensure that the tuning observed was solely due to the change in spatially indirect transition energy as a function of electric field and not due to, for example, heating effects, the pump power was kept constant for voltages between 1.5 and −0.3 V. Note that the relative intensities of the spectra in this figure have been scaled so that the different curves do not overlap. Actually, the output power monotonically decreases with increasing fields. Nevertheless, within the linear tuning range the actual output powers were within a factor of two. For voltages less that 0.3 V however, the output power fell precipitously because of a sharp increase in the lasing threshold.

Our results show that it is possible to apply useful electric fields across quantum wells even at the high carrier densities that are necessary for lasing. Nevertheless, screen-

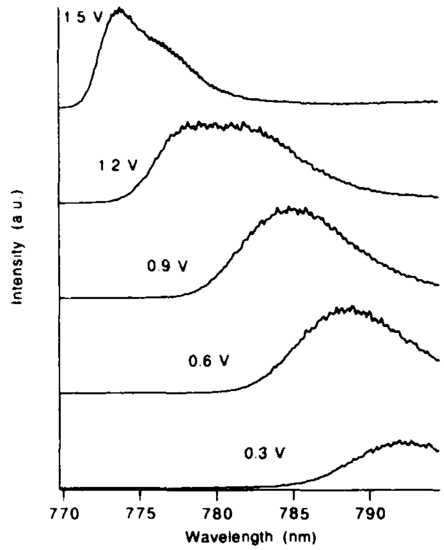

FIG. 3. Low-temperature (5 K) photoluminescence spectra under low excitation for various applied voltages for the same device as in Fig. 2.

ing of the external field by the spatially separated carriers is evident. Figure 3 shows PL spectra taken at low power excitation from 1.5 to 0.3 V. At 1.5 V, the peak of the PL is 773.8 nm while at 0.3 V the peak, though weaker, is at 792.3 nm. This shift corresponds to an effective electric field of about 68 kV/cm. Note from Fig. 2 that the lasing wavelengths for the same voltages are 773.5 and 779.2 nm. Thus, the tuning range of the low power PL is approximately 3 times that of the tuning of the laser spectra, implying that only $\simeq 27$ kV/cm, or about 40% of the externally applied field, remains effective. By increasing the external field one can tune the lasing wavelength another 2 nm, suggesting that the limitations imposed by carrier screening can be partially countered by even further increases of the applied fields.

As Fig. 2 shows, tuning is ultimately saturated at -1.2 V. Most probably, screening—combined with tunneling—is also behind this saturation. At high fields, there is an excess of holes in the wells that have been left behind by the faster electrons tunneling out. These holes cause an increase in the amount of screening without contributing much to the gain. A quantitative analysis of the saturation of the effective field as well as the screening process would involve a thorough investigation of the actual tunneling rates and carrier densities present in our experiment.

The observed tuning range is limited by tunneling and should increase significantly with an improved sample design. Optimization of the structure should provide better carrier confinement in the wells, delaying the onset of saturation and limiting potentially damaging photocurrent. The design of structures with lower threshold carrier densities should diminish the effects of screening and consequently improve both the rate and range of tuning. This prediction is supported by a comparison of the above results on coated devices with identical measurements on uncoated structures. On the uncoated devices, tuning was limited to 4.0 nm and the tuning rate was smaller due to the higher threshold carrier densities and hence increased screening. Nonetheless, aside from the decrease in tuning range, the general tuning characteristics of the uncoated device were similar to those of the coated device.

In terms of practical devices, room-temperature operation is essential. Towards this end, we have done temperature-dependent measurements and observed tuning with the coated device of 2 nm at 85 K. In this case, the tuning range was limited by our available pump power and unoptimized heat sinking. Ultimately, room-temperature operation will require that the spatially indirect transition remains dominant. In our present structure, the direct transition begins to dominate the emission at around 170 K. This behavior is due to two separate effects. First, as the temperature increases the states which contribute to the direct transition become more and more populated as compared to the lowest energy indirect transition. Second, because the radiative lifetime of the direct transition is much shorter than that of the indirect transition,[6,7] it tends to suffer a smaller decrease in total luminescence as the nonradiative lifetime of the carriers decreases with increasing temperature. Thus, successful room-temperature operation entails careful design of the sample structure to maximize the nonradiative carrier lifetime and the energy separation of direct and indirect transitions.

In conclusion, we have demonstrated that a field-effect laser in which the field is applied directly to the active region to tune the wavelength of stimulated emission is indeed feasible. By imbedding a coupled-quantum well into a GRINSCH structure, we have shown tuning of over 7 nm. Using a coupled quantum well to diminish the necessary fields to produce significant tuning is key to overcoming screening limitations. Improved structure designs should lead to higher temperature operation and larger tuning ranges and may well lead to novel optoelectronic applications.

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